MULTI-FIBER SPECTROSCOPY WITH WIDE-FIELD TELESCOPES

F. G. Watson

Royal Greenwich Observatory,

ABSTRACT: Fiber-fed multi-object systems are now the preferred instruments for gathering spectroscopic data on survey scales. The technique lends itself particularly well to telescopes with fields of 30 arcminutes or more. This paper gives a broad overview of the instrumental considerations involved in its implementation.

1. INTRODUCTION

The use of low-loss optical fibers to rearrange a randomly-distributed set of target objects for multi-object spectroscopy has become a well-established technique over the last dozen or so years. It provides one of the most efficient means of marrying a telescope with a wide field of view (which may be large in linear dimensions) to an array detector.

The astronomical problems that can be addressed by a particular system are determined as much by the telescope's field as its aperture. For any telescope feeding a multi-fiber system, the greatest attainable number-density of a particular class of target object is the density at the telescope's limiting magnitude for spectroscopy, broadly determined by its aperture. In practice, this is usually greater than the number of available fibers. On the other hand, the lowest number-density at which all the available fibers can be used depends primarily on field-of-view. Thus, field is crucially important in delineating the useful number-density range over which the system can work (see Dawe and Watson 1984, Watson 1994a). It is this consideration that has driven designers of multi-fiber spectroscopy systems for four-m class telescopes towards prime focus (e.g. Jenkins et al. 1993, Gray et al. 1993).

While detector format determines the number of fibers that can be used to feed a given spectrograph, there is no intrinsic reason why multiple spectrographs should not be operated simultaneously. The limit on the number of fibers in a multi-object system is usually set by the practicalities of packing them into the telescope's focal surface. Only for the more sparsely-distributed object-classes is the fundamental limit mentioned above approached.

There is a related technique - area spectroscopy of single resolved objects using fiber image-dissectors - for which the requirements are rather different. Here, field-size becomes subsidiary to plate-scale, though it remains important for the acquisition of guide stars. Area coverage and spatial resolution are dictated by the number of fibers, which, in turn, is generally determined by spectrograph design and detector format, since multiple spectrographs are not normally contemplated for this technique.

This paper reviews some of the technical considerations associated with multi-object spectroscopy using optical fibers. Some aspects of fiber-fed area spectroscopy are also described.

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2. FIBER FEEDS

2.1 Fiber Properties

It is the excellent transmission properties of fused silica fibers that have endeared them to astronomers. The high OH^- type ("wet" fibers) have very good blue performance at the expense of uniform transmission in the far-red, where deep OH^- absorption bands occur (see, e.g., Nelson 1988). Low OH^- fibers, on the other hand, have a flat, very high transmission profile out to approximately 2 μm. A new, hydrogenated "dry" fiber type promises wide-band performance, having the enhanced blue transmission normally associated with wet fibers.

Beyond 2 μm, other materials are needed. Fluoride glasses transmit reasonably well to ~ 4 μm (e.g. Levin et al. 1988, Levin et al. 1993, Dallier et al. 1993), while beyond that, chalcogenide glasses offer a window centered on 6 μm. These materials are less robust than fused silica.

A well-known property of all fiber types is focal ratio degradation (FRD), or beamspreading, due to microbends, internal scattering, applied stresses and diffraction (see, e.g., Ramsey 1988). Fused silica fibers with excellent FRD properties are now available. Though FRD affects slower beams ($\lesssim$ f/5) more than the fast ones found at prime foci, there are serious potential losses when the beam speed approaches that corresponding to the numerical aperture of the fiber ($\sim$ f/2 for fused silica).

Beamspreading can also result from the axis of the incoming beam being inclined to that of the fiber, a situation that will arise in most telescopes if the fibers are simply placed perpendicular to the focal surface. The effect is quite significant; for example, a four-degree inclination will speed an f/2.8 beam to f/2.0. Only in telecentric (e.g. Schmidt) telescopes, or systems where the fibers are aimed at the telescope exit pupil rather than the center of curvature of the focal surface, will the inclination be everywhere zero.

Related to FRD are the image-scrambling properties of fibers. Good FRD characteristics are associated with poor radial-scrambling of an image formed on the fiber input face for beams faster than f/5 (Barden et al. 1993, Watson and Terry 1993). The azimuthal scrambling is essentially perfect, so that an off-axis point source on the input face is transformed into a ring on the output face. These scrambling effects have implications for the illumination of fiber-fed spectrographs.

2.2 Matching

A number of considerations, often conflicting, govern the choice of fiber diameter for a given telescope and spectrograph combination. Clearly, if the fiber is to be used without any auxiliary optics (e.g. microlenses), its diameter is determined at the input end by the telescope plate scale, and at the output end by the detector pixel size imaged back through the spectrograph. If the spectrograph was designed to be fed directly by the telescope (as frequently occurred in early multi-fiber systems), these will be reasonably well-matched, but the collimator will normally be overfilled because of FRD, resulting in throughput losses.

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The use of microlenses at one or both ends of the fiber offers greater flexibility of design. For example, the 153 μm fibers of the large-diameter (2.7 arcsec) feed for the prime-focus multi-fiber system of the 4.2-m William Herschel Telescope (WHT) are used without microlenses at their input ends, accepting light at the f/2.8 delivered by the prime-focus corrector (Worswick et al. 1994). At their output ends, 2 mm sapphire balls re-image each fiber face onto the pupil of the f/8.2 collimator, so that throughput is not dependent on FRD. Spectral resolution is FRD-dependent, however, since the effective slit is a pupil image (formed about 1 mm from the microlens surface) whose diameter depends on the speed of the beam emerging from the fiber. (This feed also features connectors to allow the fiber cables to be mounted permanently on the telescope; they are described by Worswick et al., 1994.)

Though it is not strictly a wide-field application, another example is provided by the SMIRFS experimental fiber system for the 3.8-m UK Infrared Telescope (Haynes and Parry 1994). Here, "dry" fused silica fibers are used for the (J,H) wavebands, and zirconium fluoride for K. The fibers couple the f/36 focus of the telescope to the matching focus of the CGS4 cooled-grating spectrometer, but have microlenses at each end so that the beam within the fiber propagates at f/5. A problem with this system is the alignment of the f/36 beam accepted by the fibers with the telescope pupil, which demands fine angular tolerances.

2.3 Area Spectroscopy Feeds

A parameter of interest in fiber-coupled integral-field spectroscopy is the packing fraction or filling factor, i.e., the ratio of total fiber-core area to the area covered by the array at the input end. It depends on such factors as the core/cladding diameter ratio, and mode of packing (e.g. hexagonal or rectangular). Typically it might be 50 or 60 percent. One way of improving this is by the use of lenslet arrays on the input ends; if these are used in "Fabry mode" so that the telescope pupil is imaged onto the fiber cores, the packing fraction can be dramatically increased.

Examples of area spectroscopy feeds include DensePak (Barden and Wade 1988) and HEXAFLEX (Arribas et al. 1993); several new instruments are currently planned or under construction.

3. MULTI-FIBER POSITIONERS

3.1 Fiber Alignment

Requirements for aligning a fiber set with targets in the field of a telescope are principally concerned with positioning accuracy within the focal surface. Except at very low or very high focal ratios, longitudinal and angular alignment are generally more tractable problems.

The accuracy with which fibers can be placed sometimes involves more than one component; for example, the placement accuracy of a robot within its own reference frame and the accuracy of the model relating the reference frame to the real world (see, e.g., the Autofib-2 tests reported in Watson 1994b). The other side of the coin is the accuracy with which the focal-surface positions of the target images themselves are known. This involves considerations like astrometry, telescope flexure, the distortion function of the telescope optics, and atmospheric refraction (see, e.g., Watson 1984, Donelly et al. 1993).

The various means of supporting fibers in accurate alignment with target objects are now well-known. Manual plug-plate systems like the original "Medusa" and FOCAP (Hill et al. 1982, Gray 1984) have largely given way to robotic positioners. However, plug-plates will be used for the Sloan Digital Sky Survey (Owen et al. 1994), and in the experimental infra-red SMIRFS multi-fiber system (Haynes and Parry 1994).

3.2 Multi-Actuators

Broadly speaking, robotic positioners fall into the two classes of multi-actuator and pick-place systems. Both are highly software-intensive, and demand sophisticated algorithms for fiber/target allocation, placement order, anti-collision, etc.

The prototypical multi-actuator system is MX on the Steward 2.3-m telescope (Hill and Lesser 1986); it consists of 32 computer-controlled steerable arms, each of which carries object and sky fibers at its tip. While it has the advantage of rapid field set-up, the cost is prohibitive for large numbers of fibers.

3.3 Pick-Place Systems

Focal-plane pick-place systems, in which magnetic buttons carrying the fiber ends are positioned on a ferrous field plate by a single robot, are usually known as Autofib class instruments (Parry and Gray 1986). The original Autofib was developed for the 3.9-m Anglo-Australian Telescope (AAT); the more sophisticated Autofib-2 has recently been commissioned at prime focus on the 4.2-m WHT (Parry et al. 1994, Parry Lewis and Watson 1994). Autofib-2 has the capacity to position 160 fibers, and is arranged with interchangeable fiber modules.

Since Autofib devices configure fibers sequentially, their use in the telescope's focal surface incurs a time overhead which might be substantial (about 25 minutes in the case of Autofib-2). This is avoided in an off-focus pick-place system like 2dF, the AAT's two-degree prime-focus facility (Gray et al. 1993, Taylor and Gray 1994). Here, two field plates, each with its own fiber set, are interchangeable so that one can be re-configured while the other is on the sky. If (as is usual) the reconfiguration time is less than the typical exposure time, then there is a negligible set-up overhead. The penalty for this is the need to duplicate the fiber set. 2dF has two sets of four hundred fibers, distributed equally between two spectrographs.

3.4 Hybrid Systems

One or two systems do not fit exactly into the broad categorization defined above. FLAIR II on the 1.2-m UK Schmidt Telescope (UKST) is an off-focus pick-place system that requires manual selection of target objects on the (photographic) field plate before each fiber is cemented in place by a single-shot robotic positioner (Watson et al. 1993, Bedding et al. 1993, Watson and Parker 1994). Interchangeable field-plate holders allow one to be in use on the telescope while the other is being reconfigured.

A pick-place system of unusual form is represented by the Calor Alto 3.5-m telescope's "Spaltspinne" (Pitz 1993) and its near-twin, TAUMOK (originally "Feldspinne") for the 1.3-m Tautenburg Schmidt (Pitz et al. 1993, Marx 1994). Here, there is no field plate. Instead, a steel plate surrounds the focal surface; pivoted rods with fibers on their inner tips have magnetic buttons at their outboard ends which are moved by a pick-place robot.

A focal-plane pick-place system configuring 80 fiber feeds is being developed for the FUEGOS spectrograph at the ESO VLT (Felenbok et al. 1994). The 30 arcmin (1-meter) field is patrolled by two robot heads to reduce configuration time to less than ten minutes. The "Medusa" mode of this instrument fits neither the "one fiber per object" of a conventional multi-fiber feed, nor the "one object per feed" of area spectroscopy. Rather, seven fibers per object will be fed via microlens arrays to allow a spectral resolution of 30,000 to be achieved.

4. FIBER-FED SPECTROGRAPHS

In the pioneering days of multi-fiber observing, conventional long-slit spectrographs were simply spaced back from the focal surface of the telescope to make room for the plug plate and fibers. FLAIR was the first multi-fiber system to remove the spectrograph from the telescope altogether (Watson 1986), resulting in immunity from flexure with only the most elementary mechanical construction. Because of the compactness of the UKST, this involved a fiber length of only 11 m.

While long fiber runs are entirely feasible, they do reduce blue sensitivity, and a compromise solution that is being adopted on the WHT is to place the spectrograph on one of the Nasmyth platforms, resulting in a fiber length from prime-focus of 26 m. At the AAT, blue performance has been given very high priority, so the two 2dF spectrographs are mounted on the telescope's top-end ring. One consequence of this is the use of closed-cycle coolers for the detectors rather than the conventional liquid-nitrogen dewars.

Wide-field spectrographs built especially for use with multiple-fiber feeds exhibit a range of designs. "Conventional" instruments are typified by the FISCH spectrograph for FLAIR II (Watson et al. 1993), which uses the Schmidt optical system for both collimator and camera. Likewise, the 2dF spectrographs use Schmidt-type cameras fed by off-axis Maksutov collimators (Gray et al. 1993). The disadvantage with this is that the use of the unmodified beam from the fibers drives the design of the camera to very fast focal ratios. The pupil being essentially on the grating, there is also field-dependent vignetting.

Both these drawbacks have been eliminated in the WYFFOS spectrograph for the WHT (Bingham et al. 1994), which uses the "white-pupil" design of Baranne (1988) fed by microlensed fibers. Here, the pupil of the lenticular collimator is imaged onto that of the (Schmidt-type) camera by a relay mirror; in addition, the pupil is enlarged to ease the camera design and reduce the effect of the detector central obstruction. A white-pupil design is also proposed for FUEGOS (Felenbok et al. 1994).

Other unconventional designs currently under consideration include compact, slow spectrographs fed by small-diameter fibers which are themselves fed by lenslet arrays in the telescope focus (Taylor and Parry 1994). A more radical prospect still is the development of spectrographs based on slab waveguides stacked to provide a multi-object capability (Watson 1995).

5. OBSERVING WITH MULTI-FIBER SYSTEMS

Conventional wisdom maintains that optical fibers cannot compete with multi-slit spectroscopy when working on very faint objects because of imperfect sky-subtraction. This results from inadequate sampling of the sky in the immediate vicinity of the objects, uncertainty in the transmission of the fibers, and the spatial separation of object and sky spectra on the detector. The subtraction of background scattered light is also more difficult in the multi-fiber case, particularly if the fibers are close-packed.

Investigations by, e.g., Parry and Carrasco (1990) and Barden et al. (1993), have explored the limitations of the technique, showing that better than one-percent sky-subtraction is possible. Instruments with atmospheric dispersion compensation (e.g. WHT and AAT) will extend this to higher zenith-distances. Nevertheless, the unfavorable comparison with multi-slit work still exists for the faintest objects. Full-field and high-dispersion capability remain the principal advantages of the multi-fiber technique.

Observation with fibers requires normal calibration exposures such as flat-field, dark and bias frames, and wavelength calibration spectra. In addition, fiber flat fields (to calibrate the fiber-to-fiber transmission differences and telescope/spectrograph vignetting functions) are essential. Sky exposures invariably give better results than dome flats for these.

The particular instrument and observing campaign will naturally dictate the observing strategy, but a prerequisite of all multi-fiber work is the most accurate possible astrometry. Good photometry is also desirable, since the range of magnitudes that it is possible to observe simultaneously is limited by the dynamic range of the instrument.

The end-product of a multi-fiber observing run is usually several hundred spectra; with 2dF, this will run into many thousands. As far as possible, the reduction software should be automated to cope. At the UKST, spectra are reduced using FLAIR-specific tasks within IRAF; a similar approach is being adopted at the WHT for WYFFOS data, but 2dF reductions will be carried out using specially-written software that incorporates accurate modelling of the instrument. The philosophy here is that each frame can be fully reduced while the next is being obtained.

6. CONCLUSION

Though highly selective, this survey has outlined some of the more important aspects of multi-fiber spectroscopy. The sophistication of today's instrumentation and techniques contrasts strongly with the original "Medusa". It is exactly fifteen years since that instrument was used for the very first multi-fiber observations (December 1979). Though the run yielded spectra of only eight galaxies (Hill 1988), the explosion in survey-type spectroscopic data that is now imminent will owe its existence to that first pioneering step.

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